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INVESTIGATIONS ON LIGHT AND HEAT, MADE AND PUBLISHED WHOLLY R IN PART WITH APPROPRIATION FROM THE RUMFORD FUND.

XXII.

THE EFFECT OF TEMPERATURE ON THE MAGNETIC PERMEABILITY OF IRON AND COBALT.

BY JOHN TROWBRIDGE AND AUSTIN L. McRAE.

Communicated May 13, 1885.

THESE experiments were made with a view, —

1. To repeat Professor Rowland's experiments.*
2. To determine the change of the magnetic permeability with
   - *a.* The change of temperature.
   - *b.* The variation of the size and thickness of the rings.
   - *c.* The temper of the substance.
3. To determine whether the outer layer of the substance shielded the inner layers from magnetic influence.

The method of experiment was the same as Rowland's, except that the small coil around the horseshoe magnet used to bring the needle to rest was taken out of the circuit of the induced current, and a thermal junction of copper and german silver was placed in the lamp used with the mirror galvanometer, and the circuit made through the galvanometer and a key. This circuit was independent of the induced current circuit. By closing the key, a thermal current could be sent through the galvanometer. This arrangement served the same purpose as the sliding coil on the magnet, and was more convenient.

The measurements are made in the C. G. S. system of absolute units.

The symbols used are:

H = intensity of the magnetizing force.

B = magnetic induction, or the number of lines of force passing through a unit of area.

M = magnetic permeability.

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* Phil. Mag., 1873, 1874.

T = temporary part of B.
N_0 = total number of coils on the ring magnet.
a = mean radius of the ring.
r = radius of cross-section of the ring.
γ = strength of the current.
N = number of coils on the helix.
N' = number of coils on the earth inductor.
R = radius of earth inductor.
C = deflection of earth inductor.
h = deflection of the helix when the current is reversed.
h' = deflection of the helix when the current is broken.
V = vertical force of the earth's magnetism.
δ = deflection of the tangent galvanometer.

The magnetic potential inside of a ring solenoid is

$$\Omega = -2 N_0 \gamma \theta,^*$$

where θ is the azimuth angle about the axis of the ring.

Differentiating, we have

$$\frac{d\Omega}{ds} = -2 N_0 \gamma \frac{d\theta}{ds};$$

but $\frac{ds}{d\theta} = \rho$, the distance from the axis; hence the magnetic force

$$= -\frac{d\Omega}{ds} = \frac{2 N_0 \gamma}{\rho}.$$

To find the total number of lines of force passing through any area, we find an expression for the force at a single point, and then integrate this expression all over the surface between the proper limits.

If we take a section of the ring and divide it into bars of length BC and width dx, we shall have $BC = 2\sqrt{r^2 - x^2}$, and we shall find the total number of lines of force through the section to be equal.

$$\int_{-r}^{+r} \frac{2 N_0 \gamma M}{a - x} 2\sqrt{r^2 - x^2}\, dx = 4\pi N_0 \gamma M (a - \sqrt{a^2 - r^2})$$

$$= \frac{2 N_0 \gamma}{a} M \pi r^2 \left(1 + \frac{1}{4}\frac{r^2}{a^2} + \frac{1}{8}\frac{r^4}{a^4} + \&c.\right) = \frac{2 N_0 \gamma}{a} M \pi r^2,$$

since in the rings used the parenthesis differs but little from unity.

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[*] Maxwell's Elect and Mag., sect. 681.

The magnetic induction = total number of lines of force divided by the area of the section; therefore

$$B = \frac{2\,N_0\,\gamma}{a}\,M = H_1\,M.$$

In order to obtain the magnetic induction in absolute measure, the deflections of the helix were compared with the deflection of an earth inductor in the same circuit, thus: —

$$h : C :: 2\,N \pi\, r^2 B : 2\,N' \pi\, R^2 V,$$

or

$$B = \frac{N' \pi\, R^2 V h}{\pi\, r^2 N\, C}.$$

Similarly,

$$T = \frac{2\,N' \pi\, R^2 V h'}{\pi\, r^2 N\, C}.$$

We have seen that

$$H = \frac{2\,N_0\,\gamma}{a} = \frac{2\,N_0\,\kappa \text{ tang. } \delta}{a}.$$

The reduction factors of the tangent galvanometer used in Tables I. and II. are:

$K_1 = .0582.$
$K_2 = .0625.$
$K_3 = .2902.$

The reduction factors of the tangent galvanometer used in the other tables are:

$K_1 = .008868.$
$K_2 = .01972.$
$K_3 = .0876.$
$K_4 = .4435.$

Both the tangent and the mirror galvanometer were placed upon the stone piers of the laboratory.

C is the mean of from six to ten readings; h and h' are the mean of four; and δ is the mean of four readings, two before and two after h and h' were taken.

The vertical component of the earth's magnetism at Cambridge, Mass., is 0.5406.

DIMENSIONS OF THE RINGS.

W = weight of ring in air. W_1 = weight in water. S = specific gravity.

Table.	Ring.	r.	a.	W.	W_1.	S.	No.	$N' \pi R^2$.
I.	1	.700	5.46	....	....	7.83	323	42080
II.	2	.700	5.415	....	....	7.83	343	42080
III.	3	.468	5.007	165.98	144.35	7.67	750	42080
IV.	4	.4215	4.33	119.2	104.03	7.85	332	42080
V.	4	.4215	4.33	....	....	....	313	40427
VI.	4	.4215	4.33	....	....	....	296	40427
VII.	5	.698	3.164	236.0	205.54	7.75	200	3503
VIII.	5	.698	3.164	....	....	....	200	40427
IX.	6	$r_1 = .360$ .698	3.20	175.2	....	7.75	200	3503
X.	6	.698	3.20	....	....	....	200	40427
XI.	Cobalt	.637	4.495	286.77	250.80	7.966	500	42080
XII.	Cobalt	.637	4.495	....	....	....	544	3421

TABLE I.

Iron normal. 10° C.

δ.	C.	h.	N.	H.	B.	M.
K_2 3.4	13.8	10.9	30	.424	445	1020
4.6	14.0	7.46	10	.745	901	1524
6.9	....	18.41	10	.902	2225	2465
9.1	14.1	9.53	3	1.18	3812	3221
20.9	....	8.14	1	2.83	9768	3455
35.4	....	11.01	1	5.26	13209	2512
55.85	....	13.21	1	10.9	15846	1451
69.1	14.1	14.24	1	19.0	17156	882
K_3 40.65	....	14.75	1	29.4	17700	597
51.9	14.2	15.25	1	43.8	18590	415

TABLE II.

Iron normal. —18° C.

δ.	C.	h.	N.	H.	B.	M.
K_1 2.55	13.93	3.01	20	.317	183	576
3.0	....	4.05	....	.384	246	642
K_2 3.15	13.95	6.22	....	.436	377	846
4.2	....	11.7	....	.578	710	1200
5.0	....	18.66	....	.689	1131	1604
6.15	14.1	16.36	10	.855	1963	2296
7.1	....	6.64	3	.990	2656	2684
8.3	....	8.88	....	1.156	3552	3073
9.8	....	11.73	....	1.362	4691	3445
12.05	14.0	15.37	....	1.695	6191	3655
14.15	....	18.21	....	1.988	7335	3692
16.85	....	7.07	1	2.40	8542	3562
20.75	....	8.24	....	3 00	9955	3320
33.5	....	10.75	....	5.244	12990	2480
42.9	....	11.92	....	7.365	14403	1957
K_3 27.6	13.85	13.99	....	19.96	17092	837
51.1	....	15.11	....	49.23	18456	375

TABLE III. — Dec. 27, 1884.

Iron normal. —7° C.

δ.	C.	h.	h′.	N.	H.	B.	T.	M.
K_1 5.1	9.4	1.1	0.5	45	.2365	86	78	364
6.1	....	1.4	0.7	....	.2843	109	109	385
8.4	....	2.3	1.0	....	.3933	180	156	457
12.1	....	4.0	1.6	....	.5582	313	250	548
15.0	....	6.5	2 3	....	.7120	508	360	714
18.5	....	10.8	3.1	....	.8875	844	484	952
22.8	....	22.0	4.5	....	1.116	1720	704	1541
27.6	9.3	8.5	1.2	10	1.390	3022	854	2174
30.5	....	10 5	1.4	....	1.565	3732	996	2385
37.6	9.3	16.1	1.7	....	2.045	5724	1208	2798
K_2 32.1	....	9.0	0.9	3	3.7085	10664	2132	2876
35.4	....	9.7	1 0	....	4.203	11500	2370	2735
38.0	....	10.3	1.2	....	4.617	12200	2844	2645
41.4	....	11.0	1.3	....	5.210	13050	3080	2503
45.0	....	11.6	1.45	....	5.910	13750	3440	2327
48.9	....	12.3	1.6	....	6.770	14570	3790	2153
53.0	....	12.95	1.8	....	7.841	15350	4264	1958
K_3 19.6	9.2	13.75	1.95	....	9.502	16574	4672	1734
24.5	....	14.5	2.2	....	12.206	17380	5272	1423
31.4	....	15.25	2.6	....	16.03	18260	6230	1140
43.7	....	16.3	3.0	....	25.08	19533	7188	779
53.5	....	16.8	3.3	....	35.475	20130	7906	567
K_4 20.0	....	17.3	3.7	....	48.377	20723	8866	428
25.0	9.2	17.6	4.1	....	61.930	21018	9824	340

TABLE IV. — Dec. 26, 1884.

Iron magnetic. 15° C. Heated to red heat and allowed to cool slowly.

δ.	C.	h.	h′	N.	H.	B.	T.	M.
K_1 8.1	9.5	0.6	....	30	.1945	86	....	441
9.5	9.5	1.4	....	45	.227	133	....	587
11.2	....	1.7	....	....	.269	162	....	601
24.6	....	7.7	2.4	....	.623	734	458	1150
34.1	....	24.3	3.1	30	.919	3474	886	3779
52.1	....	19.2	1.6	10	1.793	8234	1372	4592
57.1	....	21.2	2.1	....	2.100	9090	1800	4330
K_2 57.5	9.5	8.6	0.7	3	4.75	12300	2000	2590
70.6	....	10.0	1.5	....	8.596	14300	4290	1663
K_4 9.4	....	10.3	2.1	....	11.13	14720	6000	1331
18.8	....	10.6	....	....	23.13	15000	....	649
26.8	....	11.0	....	....	34.43	15720	....	457
32.1	....	11.2	2.4	....	42.7	16000	6860	375

TABLE V. — April 18, 1885.

Iron magnetic. 18° C. Hardened.

δ.	C.	h.	N.	H.	B.	M.
K_1 4.6	5.5	0.25	45	.100	40	385
13.65	....	1.35	....	.311	214	686
20.4	....	2.7	....	.477	427	896
32.55	....	9.2	....	.818	1455	1780
43.95	....	17.6	....	1.236	2785	2254
K_3 10.5	....	10.4	16	2.34	4630	1975
16.45	....	14.0	....	3.74	6230	1665
26.3	5.5	18.5	....	6.26	8230	1315
33.7	....	20.95	....	8.45	9320	1105
42.5	....	24.5	....	11.6	10900	940
55.0	....	8.2	5	18.1	12100	669

TABLE VI. — April 20, 1885.

Iron magnetic. 20° C. Softened.

δ.	C.	h.	N.	H.	B.	M.
K_1 15.25	5.4	3.2	45	.331	516	1560
26.55	....	13.25	....	.606	2185	3520
36.55	....	7.2	10	.902	5220	5790
49.15	....	12.1	....	1.40	8770	6260
K_3 16.6	....	17.5	....	3.57	12700	3550
24.55	....	18.8	....	5.47	13640	2490
41.75	5.4	5.8	3	10.7	14000	1310
57.55	....	6.1	....	18.8	14750	783

TABLE VII. — April 13, 1885

Iron normal. 18° C.

δ.	C.	h.	h′.	N.	H.	B.	T.	M.
K_1 5.7	12.9	11.8	5.1	25	.112	45	39	404
8.5	....	20.1	8.3	....	.168	77	64	460
10.6	....	27.0	....	....	.210	104	....	494
13.4	....	14.1	5.95	10	.267	135	114	509
18.4	....	22.6	9.3	....	.373	217	178	581
22.0	....	8.4	3.5	3	.453	269	224	593
26.5	....	11.7	4.75	....	.559	374	304	669
33.5	....	18.2	7.1	....	.742	582	454	784
38.5	....	25.5	8.6	....	.892	815	550	914
K_3 7.25	....	16.2	4.5	1	1.41	1554	863	1100
9.9	....	35.5	6.0	....	1.93	3405	1150	1760
13.4	4.8	24.8	3.1	1	2.64	6394	1600	2426
18.1	....	34.0	4.0	....	3.62	8766	2060	2420
30.75	1.5	13.8	1.7	....	6.59	11400	2475	1730
40.25	....	15.6	2.2	....	9.38	12850	3200	1370
45.4	....	16.3	....	....	11.2	13450	....	1195
52.4	....	17.1	....	....	14.4	14100	....	980
59.8	....	17.9	2.9	....	19.03	14800	4210	776

TABLE VIII. — April 17, 1885.

Iron magnetic. 18° C.

δ	C.	h.	h′.	N.	H.	B.	T.	M.
K_1 5.7	5.5	0.25	....	30	.112	22	....	193
10.9	....	0.55	....	....	.215	48	....	221
20.25	....	1.4	....	....	.414	121	....	293
30.05	....	2.5	....	....	.648	216	....	334
41.0	....	5.26	....	....	.974	455	....	467
K_3 8.4	....	20.3	....	....	1.64	1755	....	1073
11.1	....	14.6	....	10	2.17	3790	....	1750
15.0	....	24.1	....	....	2.97	6260	....	2100
22.55	....	10.45	....	3	4.60	9040	....	1970
34.35	....	13.05	....	....	7.57	11300	....	1490
49.9	....	15.1	....	....	13.17	13100	....	993
58.6	....	16.15	....	....	18.14	14000	....	770
K_4 19.0	5.5	5.4	.875	1	19.3	14000	4540	727
29.5	....	5.625	.975	1	31.7	14600	5060	460
35.5	....	5.85	1.1	....	40.0	15200	5710	379
40.6	....	5.925	1.1	....	48.1	15400	5710	320

TABLE IX. — April 13, 1885.

Hollow iron ring, normal. 18° C.

δ.	C.	h.	h′.	N.	H.	B.	T.	M.
K_1 5.2	12.9	4.7	2.0	25	.101	25	21	242
8.2	....	8.85	3.6	....	.162	46	38	286
10.85	....	13.6	5.3	....	.215	71	55	331
16.1	....	9.7	3.5	10	.324	127	98	391
18.6	....	12.0	4.7	....	.377	157	120	416
24.1	....	5.8	2.1	3	.501	253	183	504
26.5	....	6.9	2.7	....	.559	301	235	537
33.7	....	13.3	3.9	....	.748	579	340	775
38.65	....	21.3	5.4	....	.897	928	470	1035
K_3 7.4	....	15.5	2.7	1	1.44	2025	706	1405
10.3	....	28.8	....	....	2.01	3764	....	1870
13.9	4.8	16.8	2.2	....	2.74	5900	1540	2206
18.1	....	21.3	2.8	....	3.62	7480	1970	2070
31.0	1.5	9.0	1.5	....	6.65	10100	2980	1520
40.1	....	10.05	1.8	....	9.32	11300	3570	1210
45.25	....	10.7	....	....	11.2	12000	....	1076
52.55	....	11.3	2.2	....	14.5	12700	4360	878
58.8	....	12.1	....	....	18.3	13600	....	744

TABLE X. — April 17, 1885.

Hollow iron ring, magnetic. 18° C.

δ.	C.	h.	h′.	N.	H.	B.	T.	M.
K_1 11.0	5.5	0.3	....	30	.215	35	....	164
40.9	....	9.2	....	....	.960	1085	....	1130
K_3 8.55	....	17.5	....	....	1.65	2060	....	1250
11.1	....	10.6	....	10	2.15	3750	....	1750
14.9	....	15.4	....	....	2.915	5450	....	1870
22.3	....	6.35	....	3	4.49	7490	....	1670
33.25	....	8.2	....	....	7.18	9890	....	1350
49.4	....	10.1	....	....	12.9	11900	....	924
58.1	....	10.8	....	....	17.6	12700	....	724
K_4 16.55	5.5	10.25	2.2	....	16.5	12100	5180	733
25.5	....	11.6	2.75	....	26.45	13700	6480	517
33.15	....	12.3	2.85	....	36.2	14500	6720	400
41.85	....	12.8	3.2	....	49.6	15100	7540	304

TABLE XI. — Dec. 27, 1884.

Cobalt magnetic. —5° C. Softened.

δ.	C.	h.	h′.	N.	H.	B.	T.	M.
K_1 8.5	9.2	0.7	0.3	50	.298	27	23	91
11.7	....	1.1	0.5	....	.410	43	39	104
22.6	....	2.3	1.1	....	.823	89	85	109
30.7	....	3.7	1.6	....	1.175	144	124	122
39.4	....	5.55	2.4	....	1.625	215	186	133
46.5	....	7.8	3.3	....	2.084	303	256	145
51.5	....	9.8	4.15	....	2.49	380	322	153
K_2 51.9	....	25.1	9.3	....	5.61	974	722	174
K_3 18.5	9.2	7.1	2.5	10	6.53	1377	970	211
24.6	....	11.4	3.5	....	7.10	2211	1358	311
31.9	....	18.4	5.5	....	12.17	3570	1978	293
41.4	....	25.4	6.95	....	17.22	4927	2678	286
50.5	....	9.5	2.65	3	23.65	6143	3426	260
K_4 20.2	....	11.5	3.35	....	36.4	7437	4332	204
28.6	....	13.6	4.2	....	53.9	8794	5432	163
40.55	....	15.35	4.9	....	84.6	9928	6338	117

TABLE XII. — April 30, 1884.

Cobalt magnetic. 20° C. Hardened.

δ.	C.	h.	h′.	N.	H.	B.	T.	M.
K_3 6.55	13.3	15.3	7.2	45	3.10	37	35	12
11.8	....	7.82	3.6	10	5.48	85	79	16
21.5	....	17.2	7.6	....	10.5	188	166	18
31.25	13.3	2.73	1.25	1	16.2	298	273	19
41.63	....	4.7	1.9	....	23.7	513	415	22
K_4 32.0	....	22.7	6.85	....	84.5	2476	1495	29
39.1	....	23.6	6.88	....	110.	2575	1500	23

All the iron rings were forged. The cobalt ring was cast.

Four of the iron rings were made from the same bar of Norway iron, and were of nearly the same size. Nos. 1 and 2 are two of them. The third was cooled down to —25° C. or —40° C. by means of liquefied nitrous oxide, and a partial curve taken. The fourth was heated up to 280° C. in liquid paraffine, and a few measurements taken. Although complete curves were not obtained at either of these temperatures, the part obtained differed but slightly from the corresponding parts of the curves of Nos. 1 and 2.

In order to prevent the insulation from being destroyed at the high temperature, the ring was completely covered, except in three places, with thin asbestos paper, and each turn of the coil was separated from the next by an asbestos string wound around the ring. Only one layer of wire was used. The small uncovered portions of the ring allowed it to take the temperature of the paraffine without materially affecting the uniformity of the winding.

From the curves of the other rings there does not seem to be any definite difference between the values of M due to the variation of the diameter or of the cross-section of the rings.

The temper of the metal seems to exercise a much greater influence upon the magnetic permeability than any other physical condition. This is shown by an inspection of Tables IV., V., and VI. for iron, and XI. and XII. for cobalt.

The iron ring 4 was heated to red heat and allowed to cool slowly, and it gave Table IV. It was then heated and plunged into cold water, and then gave Table V. We wished to see if it would regain its permeability on being softened again. It gave Table VI., in which the maximum value of M is greater than after the first annealing.

The maximum value of M for soft iron is about three times its maximum value for the same iron hardened.

The maximum value of M for soft cobalt is ten times as great as the maximum value for the same cobalt hardened.

SHIELDING OF MAGNETIC INFLUENCE.

We next wished to determine whether or not the outer layers of the ring shielded the inner layers from magnetic influence.

Professor Bosanquet* endeavored to decide this question by comparing the magnetic induction, for equal magnetizing forces, in rings of different cross-section. He said there was no shielding. It is evident from the preceding tables, that the quality of his metal would make such a large difference in the values of the induction as to completely mask the shielding effect if there were any.

We think the method tried by us more suitable to determine the question. A solid and a hollow ring were made from the same bar of iron, and of nearly the same diameter.

The hollow ring was made by cutting off a bar of the proper length, and drilling a hole along its axis. Then the tube thus formed was bent around and forged without closing the hollow. The radius cross-section was 0.698 cm., and the radius of the hollow, calculated from the equation $\pi r^2 - \pi r^2 =$ weight divided by the density, was 0.360 cm. This is what was used in the tables. After completing the experiments upon the hollow ring, it was sawed open, in order to see that it was hollow, and to measure the thickness of the shell. The diameter of the hollow was almost, but not exactly uniform, and the average of the measured values of its radius was a little larger than 0.360 cm. It seemed that the hollow had been made a little larger than the drill at and near the place where the ring had been forged. This would make B, T, and M a trifle larger in Tables IX. and X., and would make the magnetic induction and the permeability more nearly equal to those of the solid ring in Tables VII. and VIII., while it would make the difference in the temporary magnetism of the two rings greater.

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* Phil. Mag., February, 1885.

The mirror galvanometer used in Tables VII. and IX. was so sensitive that resistances had to be placed in the induced current circuit. This made the deflection of the earth inductor very small, and may probably have introduced an error. But as these tables were made especially to get the difference between the solid and the hollow ring, and as they were tried under exactly similar circumstances, the same errors would appear in both tables.

As far as this single experiment goes, it shows that the temporary magnetism is greater in the hollow than in the solid ring, consequently the permanent magnetism has a larger value in the solid ring. It also shows that the axis of the curve of the hollow ring is more inclined to the axis of M than that of the solid ring is.

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